Demo: InPhase – No-Cost Phase-based Ranging and Localization in Wireless Sensor Networks

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***Abstract*—The InPhase system demonstrates phase-based ranging and localization in Wireless Sensor Networks. Our wireless sensor nodes are equipped with an off-the-shelf IEEE 802.15.4 radio transceiver with integrated Phase Measurement Unit. The Active-Reflector-Principle allows to establish a meaningful distance in meters between two sensor nodes. Based on such distance measurements, we demonstrate real-time 3D localization of a sensor node in a Wireless Sensor Network by employing a particle filter. InPhase generates distance and location information at no additional hardware cost and implements all functionality in software.**

I. Introduction

Physical distance between nodes and location information can be valuable additions to the capabilities of a Wireless Sensor Network (WSN), especially if they come at no extra cost. InPhase allows to measure distances between Commercial Off-The-Shelf (COTS) radio transceivers with built-in Phase Measurement Units (PMUs) by measuring the phase angle of a Continuous Wave (CW) radio signal. [1], [2]

We demonstrate localization by using Atmel AT86RF233 IEEE 802.15.4 transceivers in the 2.4 GHz frequency band [3]. By employing the Active-Reflector-Principle (AR-Principle) the physical distance between sensor nodes can be measured [4]. A sensor node with unknown location (tag) measures multiple distances to nodes with known location (anchors) and reports those to a computer running the localization algorithm. A particle filter solves the localization problem based on the reported distances and the anchors' locations.

II. Related Work

The Atmel Ranging Toolbox (RTB) uses the AR-Principle with the PMU of an AT86RF233 radio transceiver [5]. However, as shown in [1], InPhase outperforms the RTB in terms of accuracy. Further, as the RTB firmware is only available as binary distribution for Atmel microcontrollers, it cannot be easily integrated with other wireless sensor hardware.

The crucial part of computing distance values from phase ranging data is the reconstruction of the slope of the measured sawtooth signal. Pelka et al. propose a method to extract the slope of the phase directly [6].

However, Gunia et al. found that the approach from Pelka et al. results in larger distance errors with increased measurement distance. Instead, they propose to use our distance estimation via autocorrelation and Fast Fourier Transformation (FFT). [7]

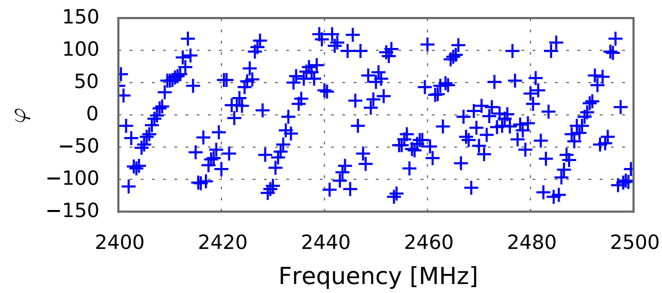

Figure 1. Raw phase response measurement (reproduced from [1])

Oshiga et al. propose a hybrid approach between the direct reconstruction from Pelka et al. and our distance estimation via FFT. A measured sawtooth signal is stacked on top of itself and a linear function is computed that fits the measurement data best. The sawtooth signal does not need to be unrolled which is error-prone for noisy data. The output of the algorithm resembles the output of our FFT and the distance is estimated similarly by search for the maximum peak in the output data. Furthermore, they propose to use multiple peaks from the result data for localization. Non-Line-of-Sight (NLOS) conditions lead to result data where the exact location cannot be determined. By passing multiple possible distances to the localization stage, the localization algorithm might still be able to localize a node. [8]

We have improved our distance estimation algorithm by interpreting the measured phase angles as a complex signal in the frequency domain. Our evaluation shows, that the new algorithm outperforms our old version and the algorithm by Oshiga et al. Further, we found that the FFT resolution can be reduced when the result is interpolated without harming accuracy and precision. [2]

III. Phase-based Ranging

InPhase exploits the AR-Principle to measure distances between sensor nodes in a WSN. The AR-Principle allows to measure a phase angle of a CW radio signal without synchronized reference clocks at the sender and receiver. One node, the initiator, starts a measurement by sending a message to a second node, the (active) reflector. When both nodes agreed on the measurement parameters, a measurement of a signal's phase angle is executed over a spectrum of multiple frequencies. Figure 1 shows a resulting sawtooth signal. The

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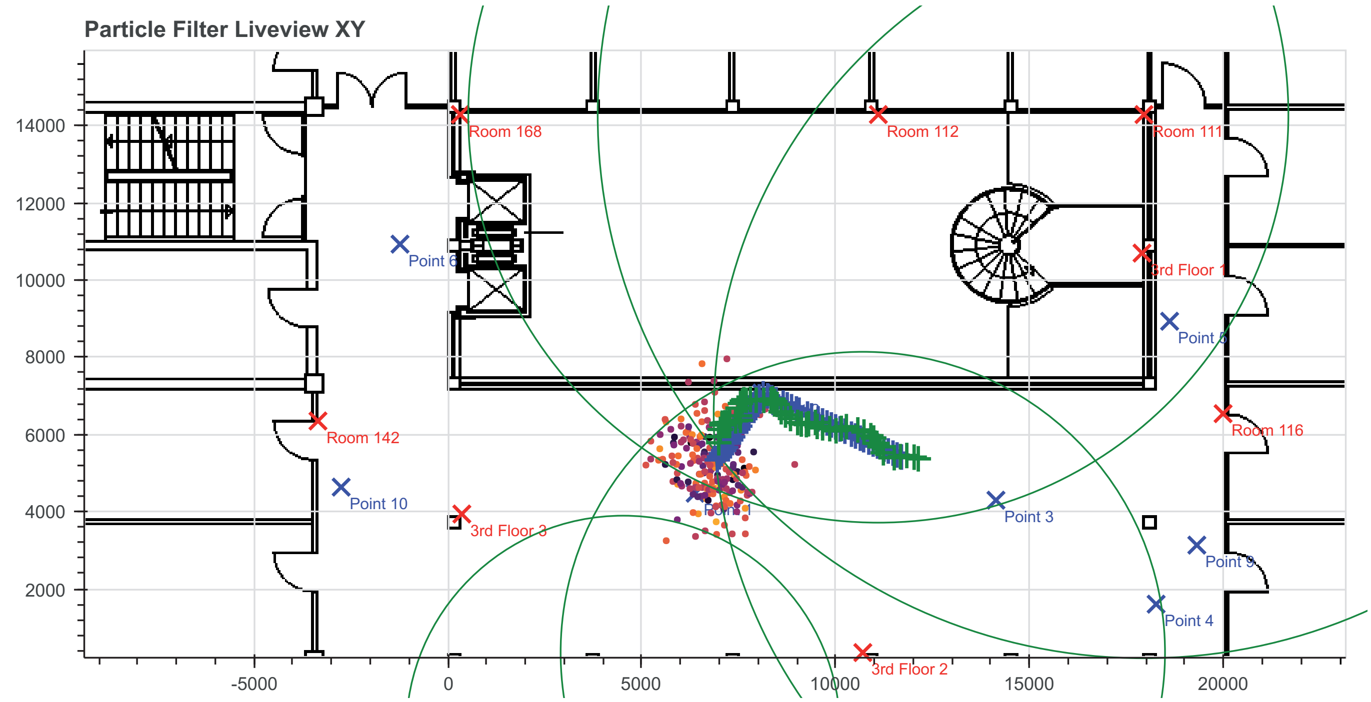

Figure 2. Visualization of the localization algorithm. Red x's: Anchor nodes. Blue x's: Known reference points. Green Circles: Measured distances. Blue +-symbols: Ground truth path. Green +-symbols: Localization output. Orange point cloud: Particles. Both axes are marked in millimeters.

Figure 3. Battery-powered InPhase sensor node.

steepness of the slope is proportional to the distance between both nodes. The distance can be computed via our algorithms presented in [1] and [2].

The new algorithm [2] allows to measure distances up to 300 m. However, as the maximum transmission range of wireless sensor nodes is restricted by the allowed maximum output power, this distance is not achieved in practice. We were able to measure distances up to 275 m with our hardware.

IV. Localization

To localize a sensor node, distances to sensor nodes (anchors) in known reference locations are measured. The sensor node to be localized (tag) initiates distance measurements with all anchors in a round-robin fashion and reports the measurements to an attached computer.

In the next step, distances from the obtained measurements are computed and consumed by a particle filter to localize the tag in 3D space. The particle filter has prior knowledge of the system via the positions of the particles from the last round and reports 3D coordinates. Each new measurement updates the location estimation by re-evaluating the particle positions and their likelihood to be in the correct location.

Figure 2 shows the output visualization of the system. In the background, a 2D map of the area is shown. The positions of reference anchors are marked with red x's and known ground truth locations are marked with blue x's. The particle cloud is displayed as a scatter plot of filled circles. The different colors indicate the probability of that particle. Lighter colors indicate higher probability. The green circles indicate the measured distances around the anchors. Blue +-symbols indicate the ground truth path that was taken, while green +-symbols indicate the reported location. Both of these plots have a short trace of previous positions to indicate the path that was taken.

V. InPhase Sensor Node

Our own battery-powered wireless sensor node is used for the demonstration, see Figure 3. It is based on the INGA wireless sensor node [9] and uses an ATmega1284p microcontroller [10]. The AT86RF233 radio is mounted on an extra

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Figure 4. Panoramic view of the evaluation area of the Microsoft Indoor Localization Competition 2018.

circuit board to allow different experimental setups with other radio chips. The radio board features an SMA connector for experiments with different antenna designs.

Although we use our own modular sensor node, it does not feature any special hardware. Thus, InPhase remains a solution that requires only additional software on a sensor node and no extra hardware.

VI. Real-world Setup and Evaluation

The InPhase system competed in the Microsoft Indoor Localization Competition 2018 [11]. We deployed a total of 10 anchors on two floors and a large staircase. Figure 4 gives an impression of the evaluation area. For the evaluation, the tag was mounted to a LIDAR scanner which was used to obtain ground truth measurements [12]. During evaluation, a person walked along a previously secret path through the whole area. Our system scored an average location error of 0.99 m.

The biggest challenge is obtaining the ground truth locations of anchor nodes in the local coordinate system. Especially in buildings with complex architectural features like columns and sloping walls, it is hardly possible to obtain measurements with a laser rangefinder. One team used a total station for ground truth measurements. This resulted in very precise reference anchor locations for their setup.

VII. Demo Setup

Multiple anchor nodes are mounted to the walls and preferably to the ceiling of the demonstration area. The ground truth location of these nodes will be measured. The duration of the offline survey is dependent on the number of tags and the complexity of the setup area. The tag node is mounted on top of a camera tripod and can be freely moved to different locations. A single-board computer relays the measurements from the tag node to a computer that runs the localization algorithm and displays the results as well as the current state of the particle filter in real-time, see Figure 2.

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